Leptonic Charm Decays at CLEO

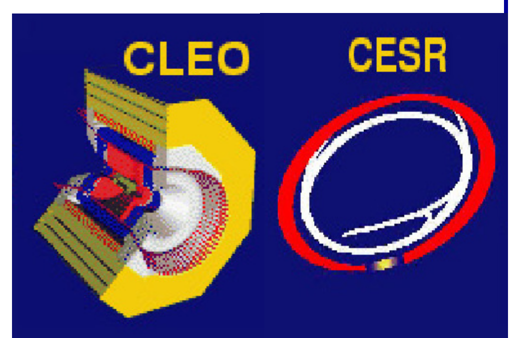
- Overview of the CLEO experiment
- D and D_S leptonic decays to $\mu\nu$ and $\tau\nu$:
  - ✓ Measurements of absolute branching fractions
  - ✓ Measurements of absolute decay constants
- Comparison with theory (LQCD)

Victor Pavlunin

on behalf of

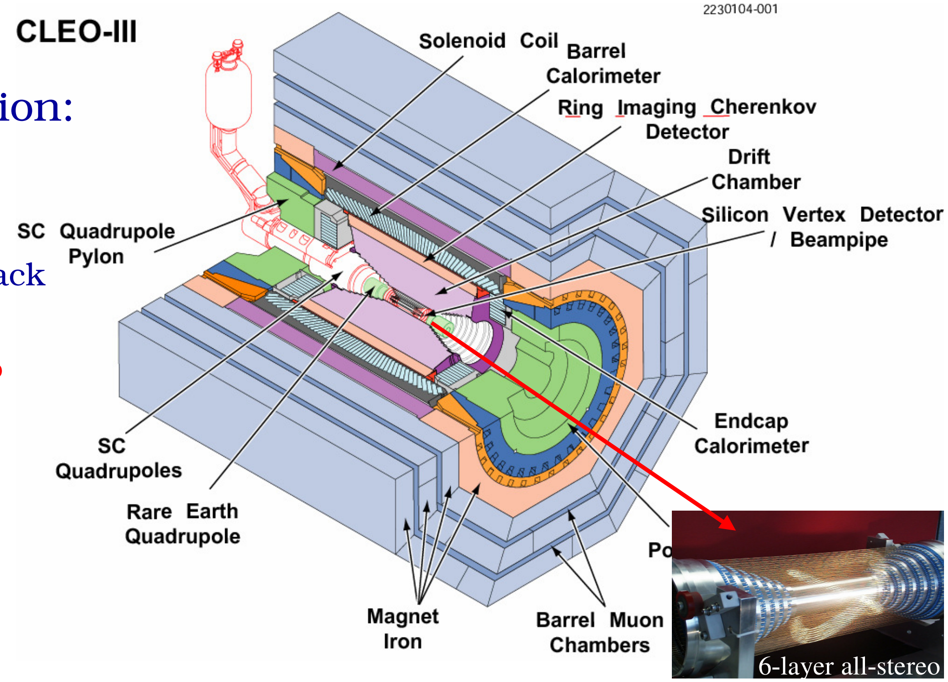
the CLEO collaboration

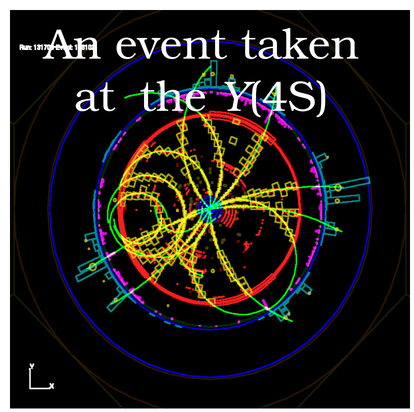
DPF-2006

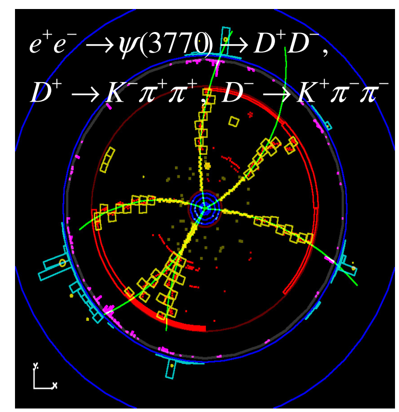


The CLEO detector

- The CLEO detector was developed for B physics at the Υ(4S). CLEO-III configuration:
  - ✓ B-field: 1.5 T
  - ✓ Gas (drift chamber): He and C_3H_8
  - ✓ Tracking: 93% of 4π, δP/P≈0.6% for a 1.0 GeV track
  - ✓ Hadron particle ID: RICH (80% of 4π) and dE/dx
  - ✓ E/M crystal calorimeter: 93% of 4π, δE/E ≈ 2.0% (4.0)% for a 1.0 GeV (100 MeV) photon
  - ✓ Muon prop. chambers at 3, 5 and 7 λ_I.
- Transition from CLEO III to CLEO-c:
  - ✓ B-field: 1.5 T → 1.0 T
  - ✓ Silicon vertex detector → low mass stereo drift chamber
- Advantages of running at the ψ(3770) for charm physics:
  - ✓ Pure DD, no additional particles
  - ✓ σ[DD at ψ(3770)] = 6.4 nb [σ(cc) at Υ(4S) ~1.3 nb]
  - ✓ Low mulitplicity, high tagging efficiency (>20%)







Why a Charm Factory?

The main task of the CLEO-c open charm program:

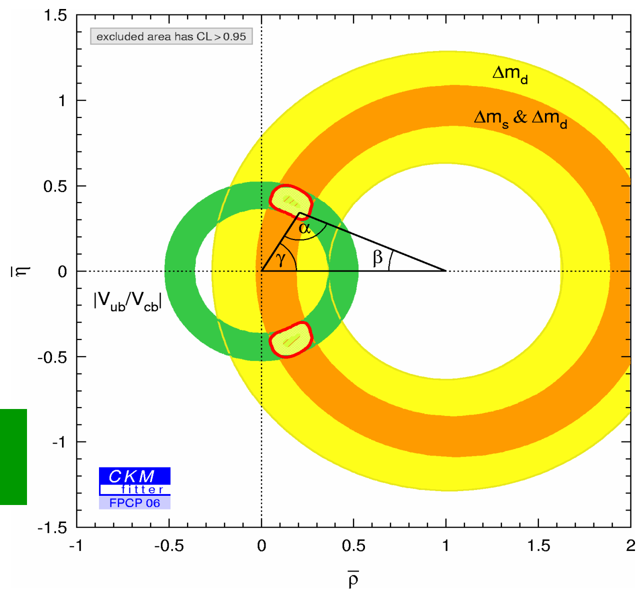
Calibrate and Validate Lattice QCD

- Help heavy flavor physics constrain the CKM matrix *now*:

  ✓ Precision tests of the Standard Model or
  ✓ Discovery of new physics beyond the SM in *b* or *c* quark decays

Difficulty: hadronic uncertainties complicate the interpretation of exp. results:

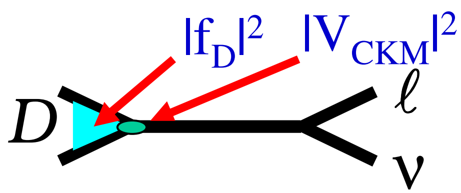
Reduce theory error on B form factors and B decay constants using tested LQCD



- Help LHC search for and interpret new physics if new physics is strongly coupled *in the future*

Examples of LQCD tests and their impact

- Leptonic decays ($D^+ \to \mu\nu$ and $D_s \to \mu\nu$):

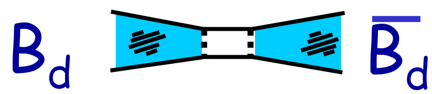


$$Rate \propto f^2_{D_{(s)}} \, |V_{cd(s)}|^2$$

Experiment

LQCD

Known to < 1% from the CKM unitarity

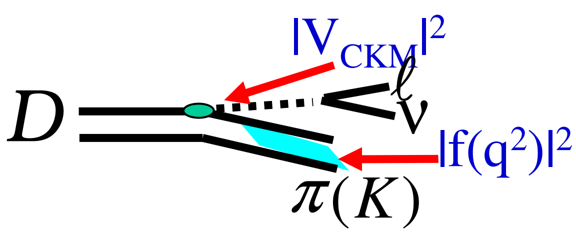


$$Rate \propto f^2_{B_d} \, |V_{td} V^*_{tb}|^2$$

Lattice predicts f_B/f_D and f_B/f_{Bs} with small errors ⇒ precise f_D gives precise f_B and $|V_{td}|$; f_D/f_{Ds} checks f_B/f_{Bs} and allows precise $|V_{td}|/|V_{ts}|$

The main topic of this talk

- Semileptonic decays ($D \to \pi e\nu$, $D \to K e\nu$):



$$Rate \propto |V_{cd(s)}|^2 |f_+(q^2)|^2, \quad \text{where} \quad q^2 \equiv M^2(e\nu)$$

Test LCQD calculations of $f_+(q^2)$ in the *D* system and apply them to the *B* system for $|V_{ub}|$ and $|V_{cb}|$

The topic of the next CLEO talk

- Combination of leptonic and semileptonic decays:

$$\Gamma(D \to \pi e\nu)/\Gamma(D \to \mu\nu) \propto f^2_+(q^2)/f^2_D$$

Test LQCD with no errors from CKM couplings

CLEO-c Data Samples

Results presented in this talk were obtained using the following data samples:

- ❑ $\psi(3770)$: total luminosity = ~ 280 pb^{-1}
- ❑ E_{CM} = 4170 MeV: total luminosity = ~ 200 pb^{-1}

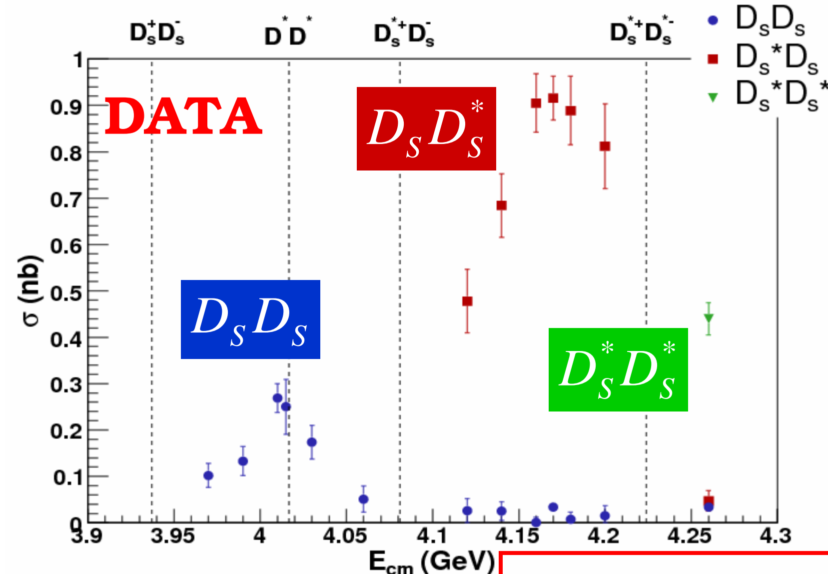
CLEO scanned E_{CM} = 3.97 – 4.26 GeV:

Optimal energy for D_s physics:

E_{CM} = 4.170 GeV

Dominant production mechanism:

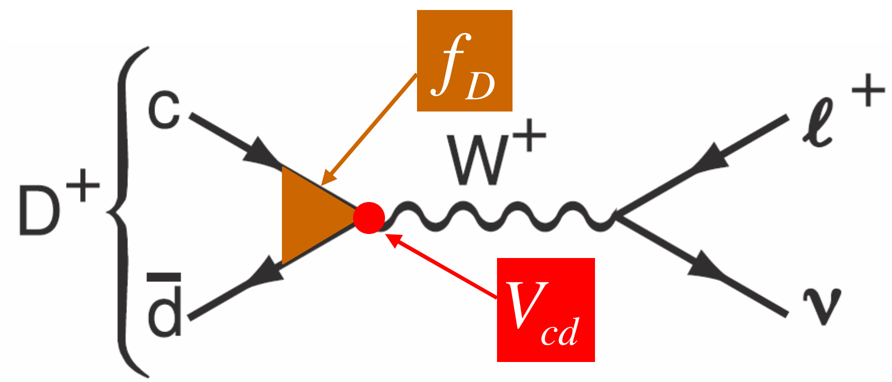
$$e^+e^- \to D_S D_S^*$$



Preliminary

- ❑ [Additional 120 pb^{-1} at E_{CM} = 4170 MeV already collected: to be analyzed]

$D_{(s)}$ Leptonic Decays



$$\Gamma(D^+ \to l^+\nu) = \frac{1}{8\pi} G_F^2 \boxed{f_D^2} m_l^2 M_D \left(1 - \frac{m_l^2}{M_D^2}\right)^2 \boxed{|V_{cd}|}^2$$

- Standard Model predicts:
  - ✓ D decays: $\Gamma(e^+\nu):\Gamma(\mu^+\nu):\Gamma(\tau^+\nu) = 2.3\times10^{-5}:1.0:2.7$
  - ✓ D_s decays: $\Gamma(e^+\nu):\Gamma(\mu^+\nu):\Gamma(\tau^+\nu) = 2.5\times10^{-5}:1.0:9.7$
- Use V_{cd} and V_{cs} to extract f_D and f_{Ds}, and compare them to theory

$D^+ \to \mu\nu$ and $D^+ \to \tau\nu$ at the $\psi(3770)$

References:

PRL **95**, 25801 (2005)
PRD **73**, 112005 (2006)

Tagging at the $\psi(3770)$

- The $\psi(3770)$ is about 40 MeV above the DD pair threshold ($\vec{P}_D = -\vec{P}_{\bar{D}}$)

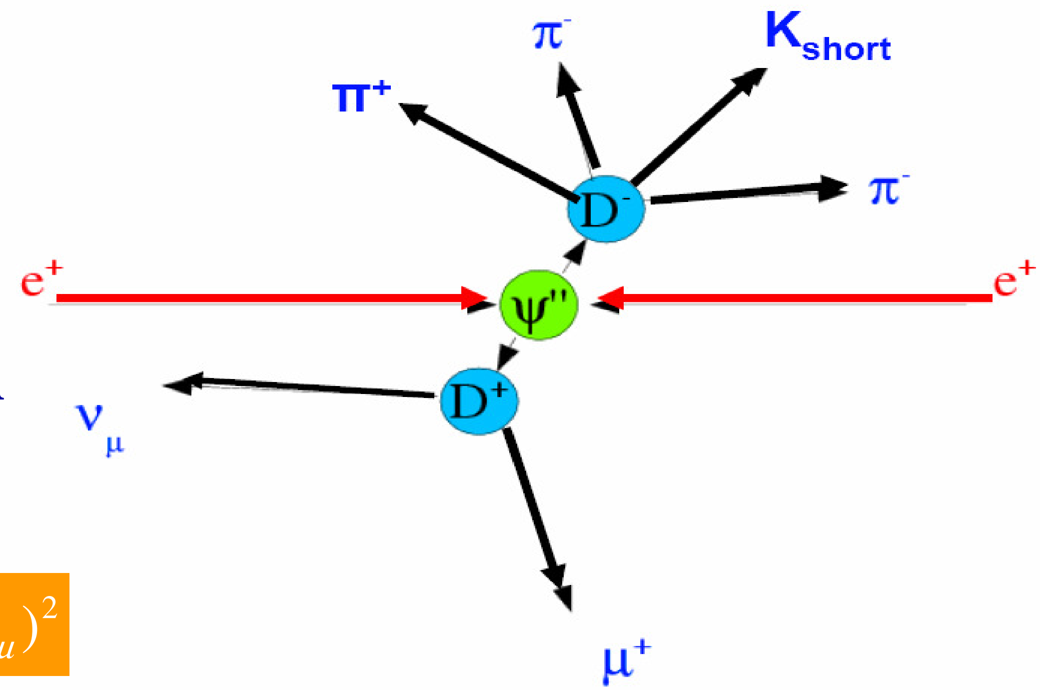
- Variables used in the tag reconstruction:

$$M_{bc} = \sqrt{E_{beam}^2 - P_{candidate}^2}$$

$$\Delta E = E_{candidate} - E_{beam}$$

- Leptonic decays are identified using missing mass squared:

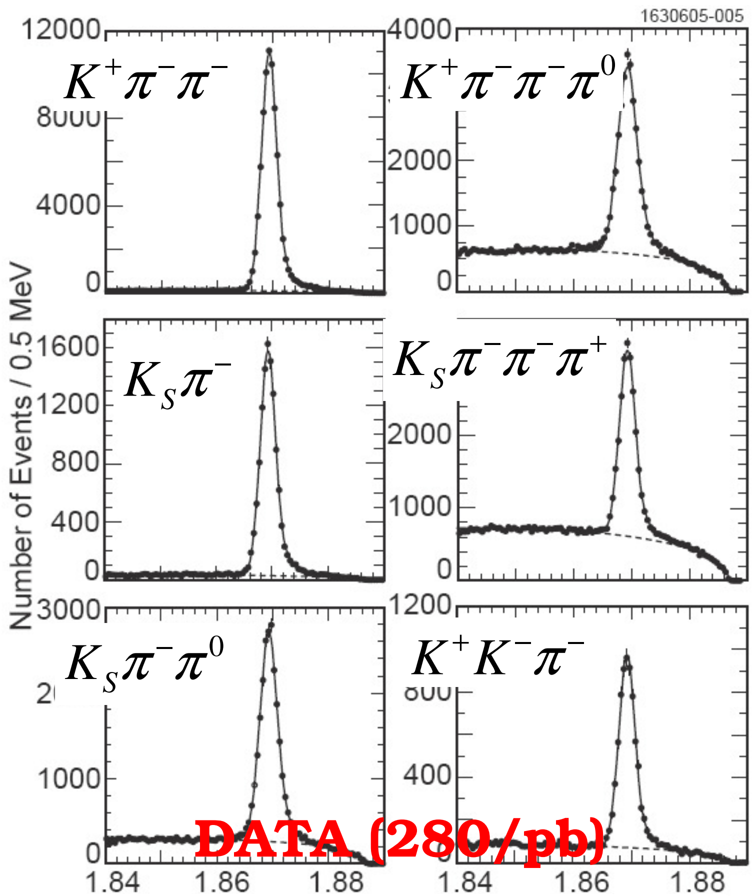
$$MM^2 = (E_{beam} - E_\mu)^2 - (-\vec{p}_{tag} - \vec{p}_\mu)^2$$



Tagging creates a **beam of *D* mesons** with known momentum

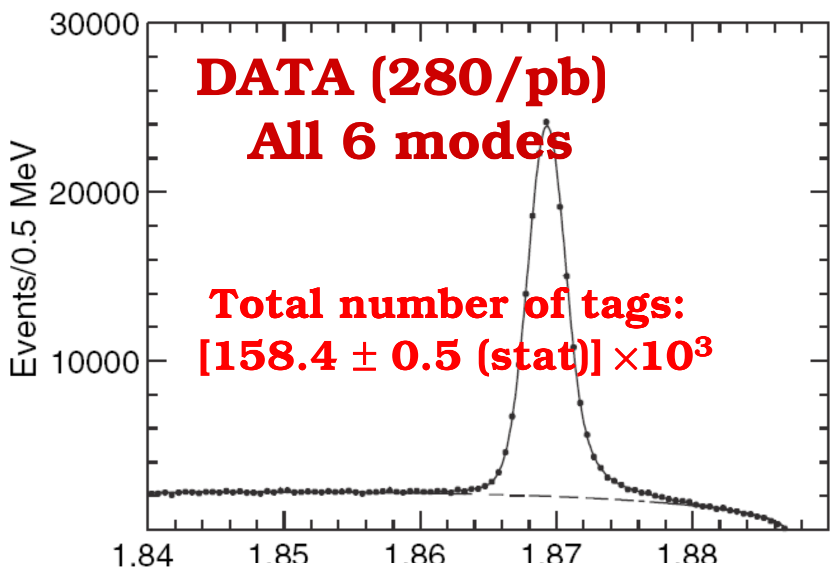
D^- Tags

Cut on ΔE and fit M_{BC}:



$$M_{bc} = \sqrt{E_{beam}^2 - P_{candidate}^2} \quad [GeV]$$

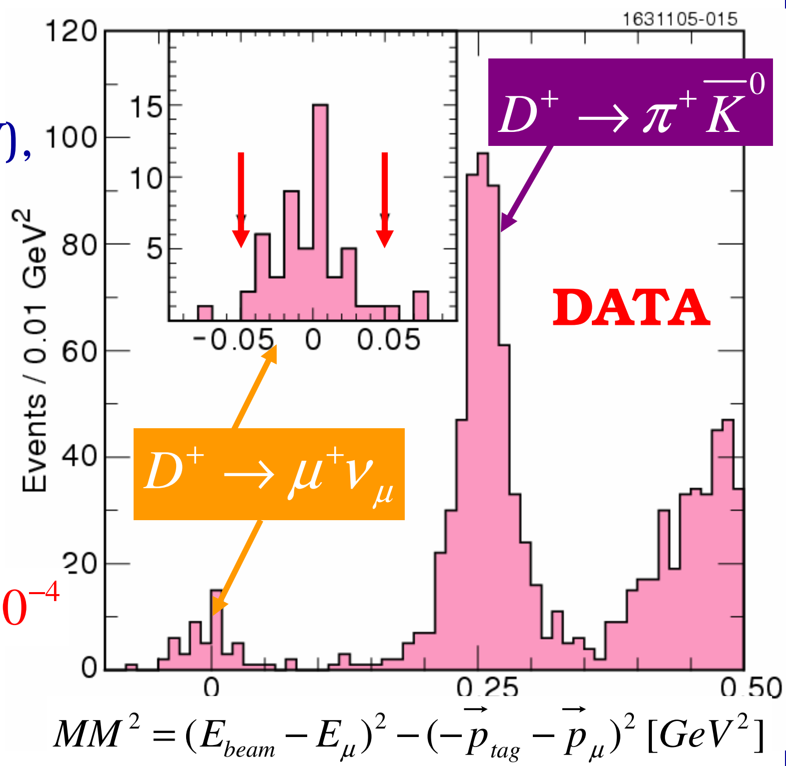
Mode	Signal
$K^+\pi^-\pi^-$	77 387 ± 281
$K^+\pi^-\pi^-\pi^0$	24 850 ± 214
$K_S\pi^-$	11 162 ± 136
$K_S\pi^-\pi^-\pi^+$	18 176 ± 225
$K_S\pi^-\pi^0$	20 244 ± 170
$K^+K^-\pi^-$	6535 ± 95
Sum	158 354 ± 496



$$M_{bc} = \sqrt{E_{beam}^2 - P_{candidate}^2} \quad [GeV]$$

$D^+ \to \mu^+\nu$ and $e^+\nu$

- Full event reconstruction:
  - ✓ require a tag,
  - ✓ require a muon cand. (E_{CC}^{track} < 300 MeV),
  - ✓ veto events with extra tracks and energy clusters > 250 MeV.
- Results:
  - ✓ 50 $D^+ \to \mu\nu$ candidates
  - ✓ Estimated bckg: 2.8 events
  - ✓ $B(D^+ \to \mu^+\nu) = [4.4 \pm 0.7(stat) \pm 0.1(syst)] \times 10^{-4}$
  - ✓ $f_{D^+} = [223 \pm 17(stat) \pm 3(syst)]\ MeV$



- The same analysis is repeated for $D^+ \to e^+\nu$. *No* signal candidates are seen: $B(D^+ \to e^+\nu) < 2.4 \times 10^{-5}$ (at 90% CL)

$D^+ \to \tau^+ \nu$

- Reconstruct $D^+ \to \tau^+ \nu$ with $\tau^+ \to \pi^+ \nu$

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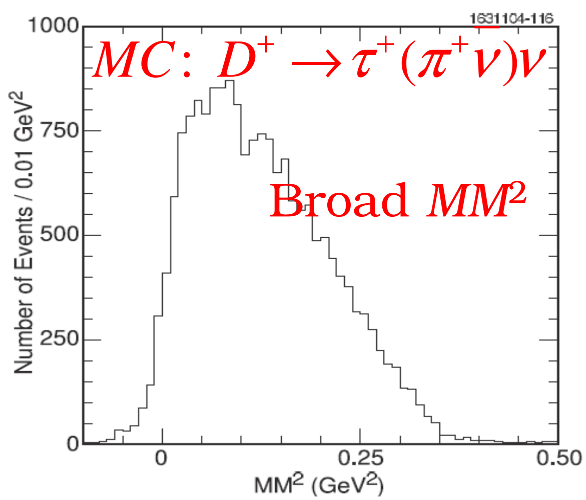
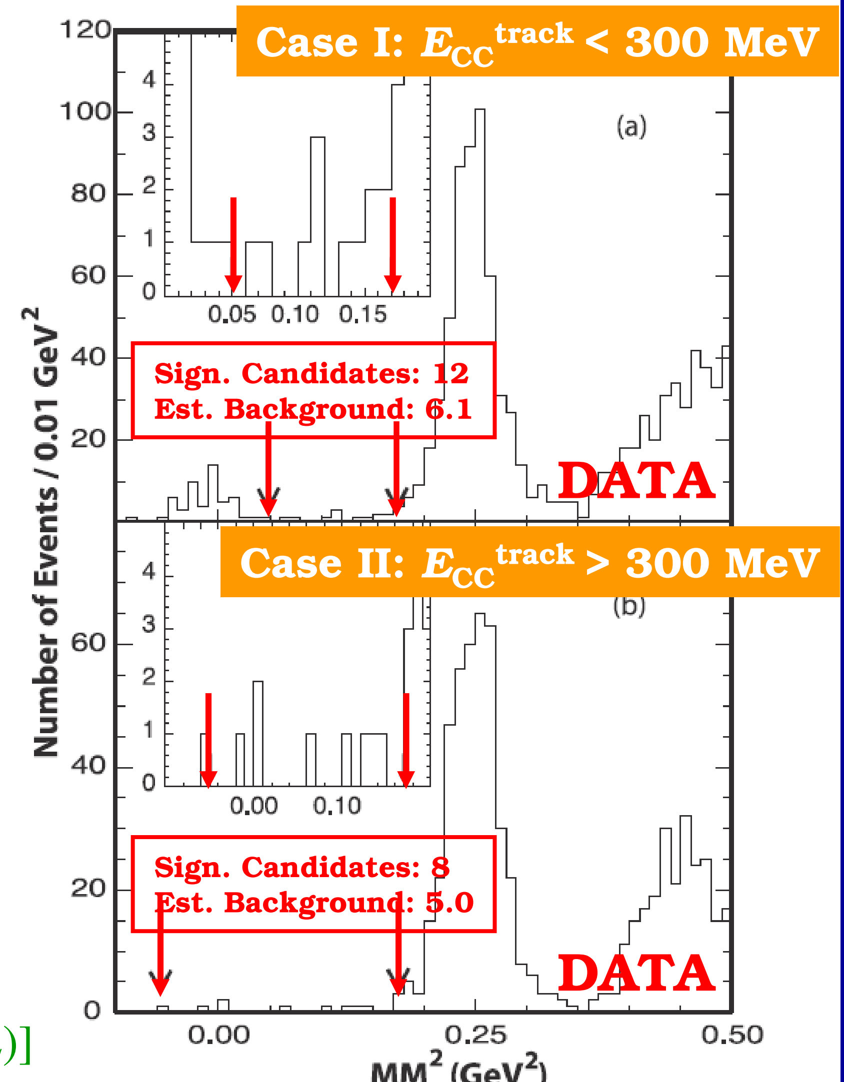




$B(D^+ \to \tau^+\nu) < 2.1\times10^{-3}$ (at 90% CL)

[$SM:\ B(D^+ \to \tau^+\nu) < (1.1\pm0.2)\times10^{-3}$ (at 90% CL)]

$D_S \rightarrow \mu\nu$ and $D_S \rightarrow \tau\nu$ at E_{CM} = 4170 MeV

References:

CLEO CONF 06-17
hep-ex/0610026

D_S Tags (1)

- Recall at E_{CM} = 4170 MeV: $e^+ e^- \to D_S D_S^*$

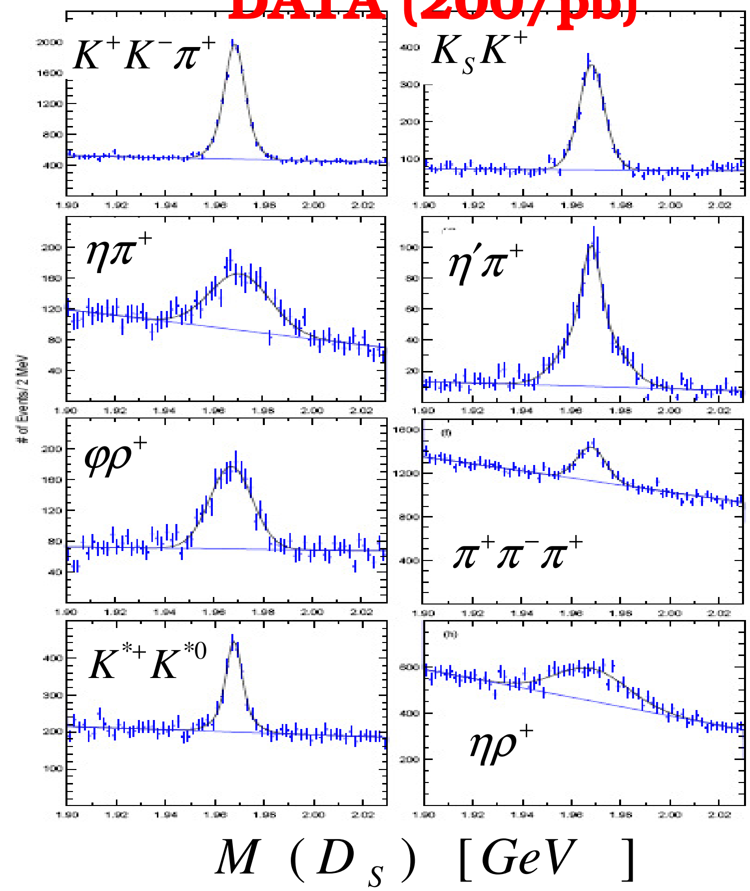
D_S^* decays to D_S via

e p s ne ⇒ M_{BC}

- T n the analysis:

Mode	Yields from M(Ds)
$K^+K^-\pi^+$	8446 ± 160
K_SK^+	1852±62
$\eta\pi^+$; $\eta \to \gamma\gamma$	1101 ± 80
$\eta'\pi^+$; $\eta' \to \pi^+\pi^-\eta$, $\eta \to \gamma\gamma$	786±37
$\phi\rho^+$; $\phi \to K^+K^-$, $\rho^+ \to \pi^+\pi^0$	1140±59
$\pi^+\pi^-\pi^+$	2214±156
$K^{*+}K^{*0}$; $K^{*+} \to K_S\pi^+$, $K^{*0} \to K^-\pi^+$	1197±81
$\eta\rho^+$; $\eta \to \gamma\gamma$, $\rho^+ \to \pi^+\pi^0$	2449±185
Sum	19185 ± 325

DATA (200/pb)

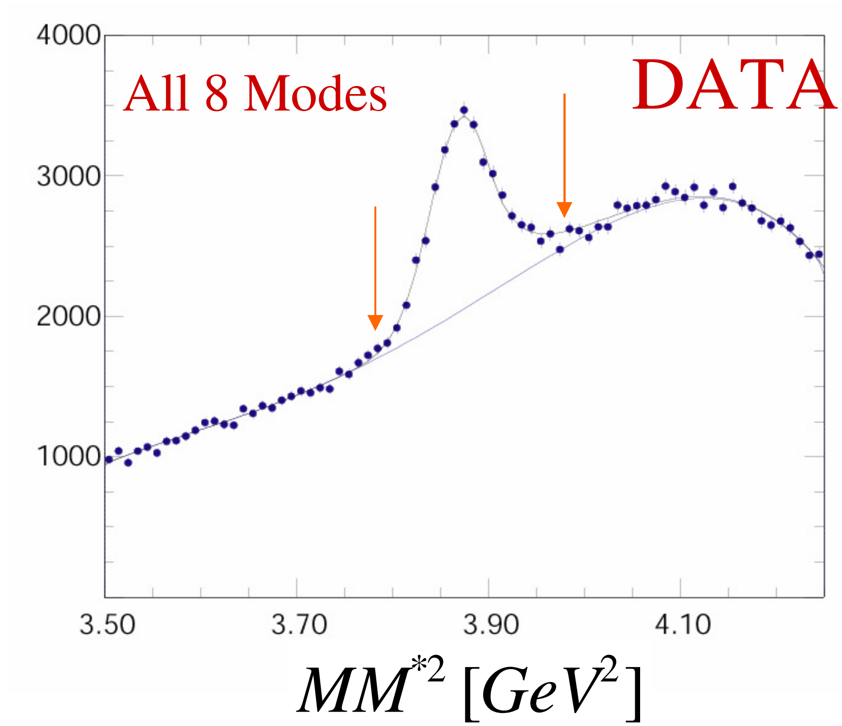


Total number of tags from $M(D_s)$: [19.2 ± 0.3 (stat)] ×10³

D_S Tags (2)

- To fully reconstruct the event, the photon must be detected. The missing mass squared can be used to obtain the number of tags:

$$MM^{*2} = (E_{CM} - E_{D_S} - E_\gamma)^2 - (-\vec{p}_{D_S} - \vec{p}_\gamma)^2$$



Total number of tags in the signal region of MM^{*2}:
[11.9 ± 0.4 (stat) ± 0.5 (syst)] ×10³

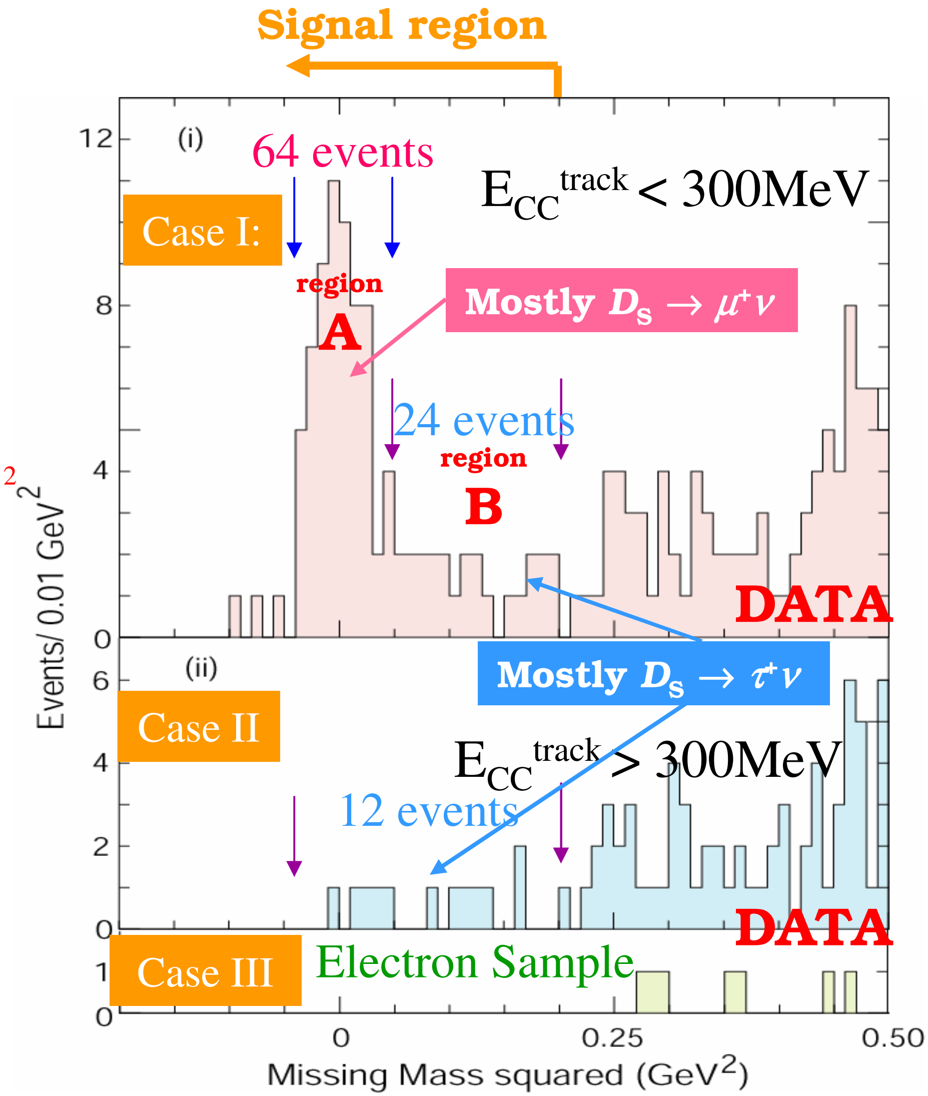
$D_S \to \mu^+\nu$ and $\tau^+(\pi^+\nu)\nu$ (1)

- **Full event reconstruction:**
  - ✓ Require a tag and a γ from D_S^*,
  - ✓ Require one additional track,
  - ✓ Veto events with E_{CC} > 300 MeV or extra tracks.
- Use MM^2 to separate $\mu^+\nu$, $\tau^+(\pi^+\nu)\nu$ and background:

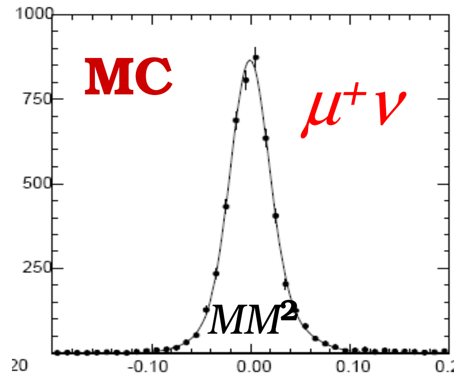
$$MM^2 = (E_{CM} - E_{D_s} - E_\gamma - E_{\mu(\pi)})^2 - (-\vec{p}_{D_s} - \vec{p}_\gamma - \vec{p}_\mu)^2$$

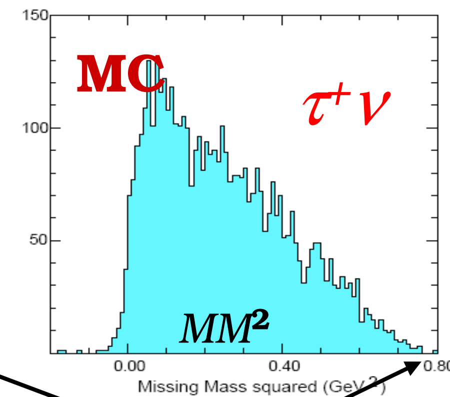
- Consider three cases:
  - ✓ Case I: E_{CC}^{track} < 300 MeV (accept 99% of muons and 60% of pions)
  - ✓ Case II: E_{CC}^{track} > 300 MeV (accept 1% of muons and 40% of pions)
  - ✓ Case III: require an electron

[Kinematical constraints are used to improve resolution and remove multiple combinations]

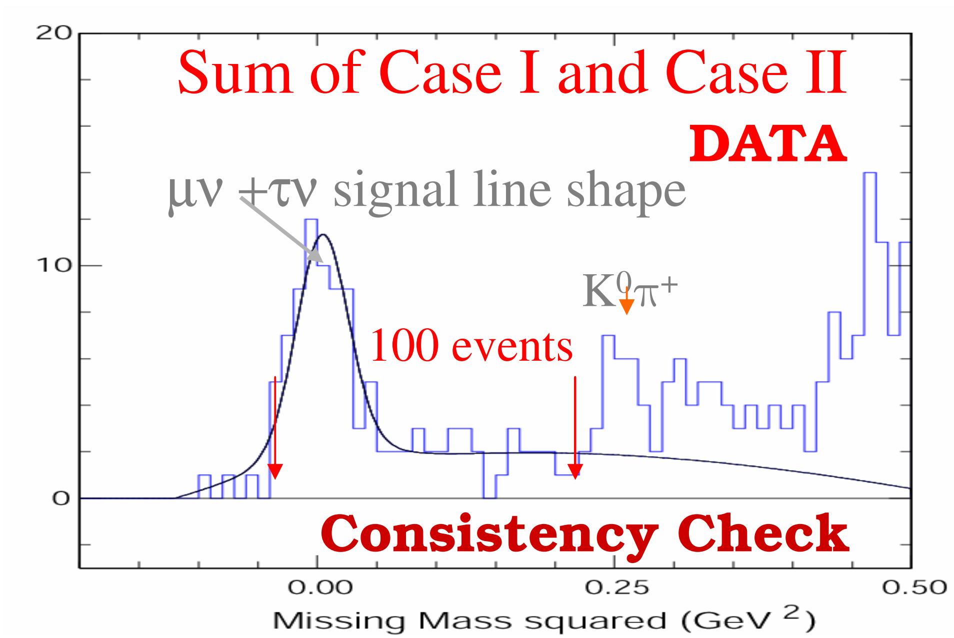


$D_S \to \mu^+\nu$ and $\tau^+(\pi^+\nu)\nu$ (2)





Note the scale limits: 0.20 and 0.80 GeV²

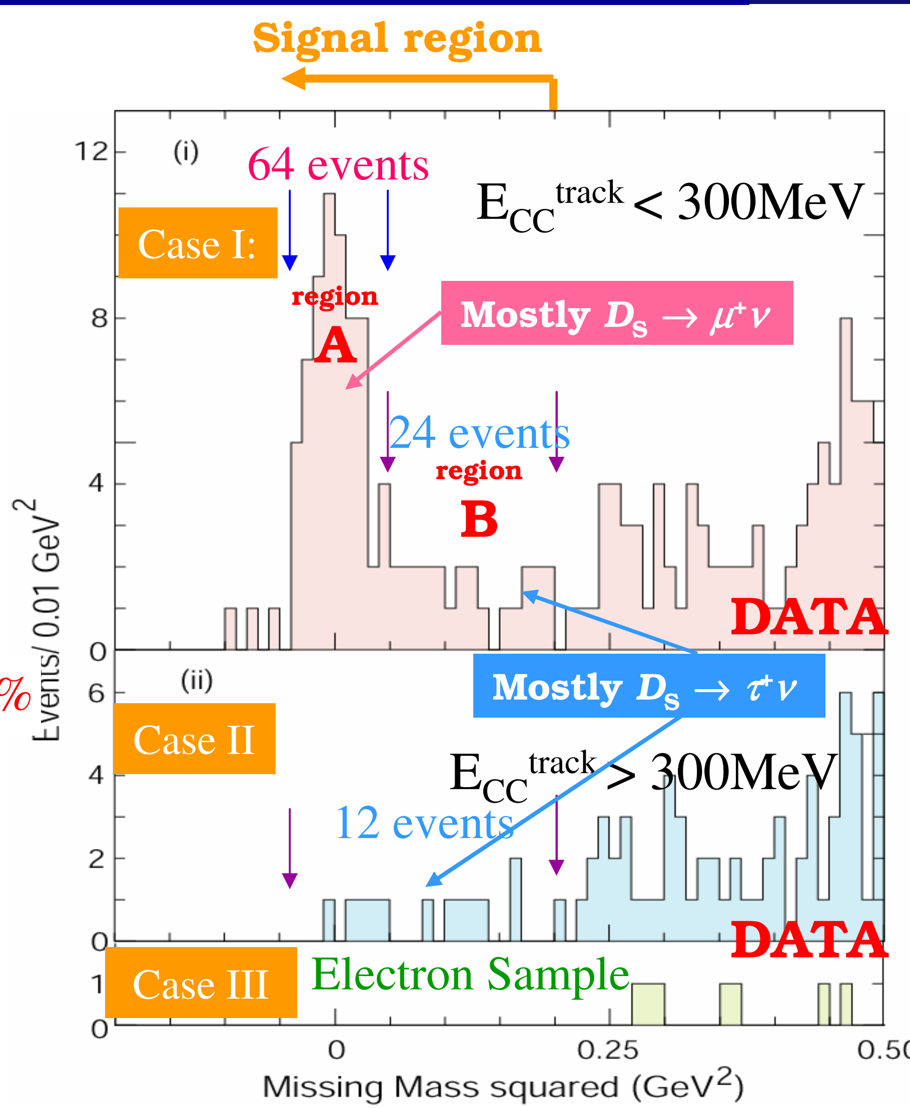


$D_S \to \mu^+\nu$ and $\tau^+(\pi^+\nu)\nu$ (3)

- $D_S \to \mu^+\nu$ (Case I, Reg.A)
  64 signal candidates, 2.0 bkg events:
  $B(D_S \to \mu^+\nu) = [0.66 \pm 0.09(stat) \pm 0.03(syst)]\%$
- $D_S \to \tau^+\nu$ (Case I,Reg.B+Case II)
  36 signal candidates, 4.8 bkg events:
  $B(D_S \to \tau^+\nu) = [7.1 \pm 1.4(stat) \pm 0.3(syst)]\%$
  $[PDG-06:\ B(D_S \to \tau^+\nu) = (6.4 \pm 1.5)\%]$
- Use the SM $\mathcal{B}(\tau^+\nu)/\mathcal{B}(\mu^+\nu)$ to average results above:
  $B(D_S \to \mu^+\nu) = [0.66 \pm 0.08(stat) \pm 0.03(syst)]\%$
  $[PDG-06:\ B(D_S \to \mu^+\nu) = (0.61 \pm 0.19)\%]$

  $f_{D_S} = [282 \pm 16(stat) \pm 7(syst)]\ MeV$
- $D_S \to e^+\nu$ (Case III):
  No signal candidates:

Preliminary $B(D_S \to e^+\nu) < 3.1 \times 10^{-4}$



$D_S \to \tau^+(e^+\nu\,\nu)\,\nu$

- Complimentary analysis:

  $D_S \to \tau^+\nu$ with $\tau^+ \to e^+\nu\,\nu$.

- $\mathcal{B}(D_S \to \tau^+\nu)\mathcal{B}(\tau^+ \to e^+\nu\nu) \sim 1.3\%$ is large [cf. $\mathcal{B}(D_S^+ \to Xe^+\nu) \sim 8\%$]

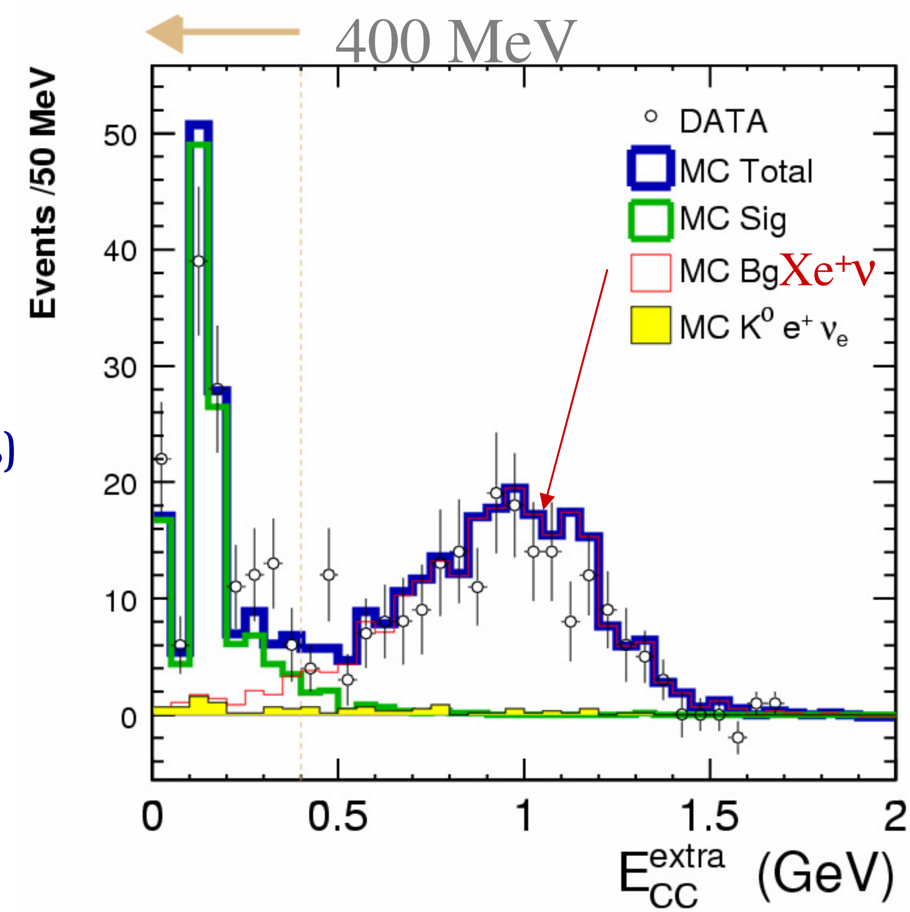
- Analysis Technique:
  - ✓ Find e^+ and D_S^- tag (γ from D_S^* is *not* reconstructed, same tag modes)
  - ✓ Veto events with extra tracks
  - ✓ Extra energy in CC < 400 MeV

- Results:

$B(D_s \to \tau^+\nu) = [6.3 \pm 0.8(stat) \pm 0.5(syst)]\%$

$[PDG-06:\ B(D_s \to \tau^+\nu) = (6.4 \pm 1.5)\%]$

$f_{D_S} = [278 \pm 17(stat) \pm 12(syst)]\ MeV$



Preliminary

Comparison with theory

Summary of CLEO-c results:

- $f_{D^+} = [223 \pm 17(stat) \pm 3(syst)]\ MeV$
- $f_{D_S} = [280 \pm 12(stat) \pm 6(syst)]\ MeV$

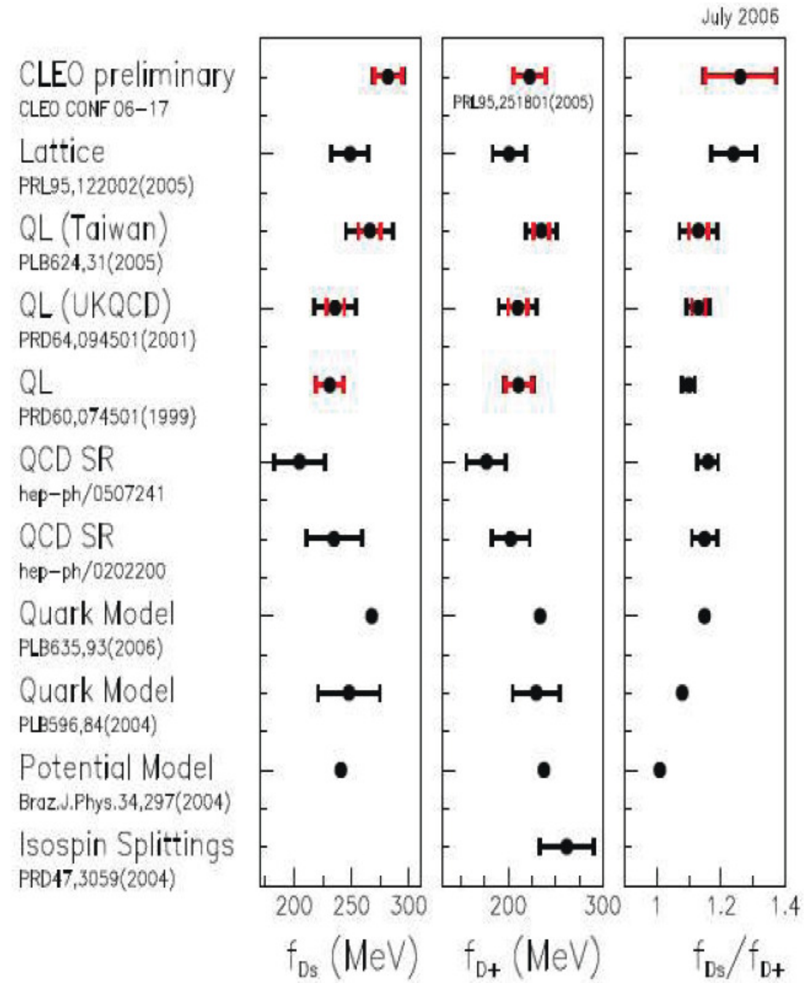
  [Weighted average; syst. errors are mostly uncorrelated]
- $\frac{f_{D_S}}{f_{D^+}} = 1.26 \pm 0.11$ **Preliminary**

CLEO-c: statistically limited

An example of theor. preditions:
Unquenched LQCD [PRL **95**, 122002 (2005)]

- $f_{D^+} = [201 \pm 3(stat) \pm 17(syst)]\ MeV$
- $f_{D_S} = [249 \pm 3(stat) \pm 16(syst)]\ MeV$
- $\frac{f_{D_S}}{f_{D^+}} = 1.24 \pm 0.07$

LQCD: systematically limited



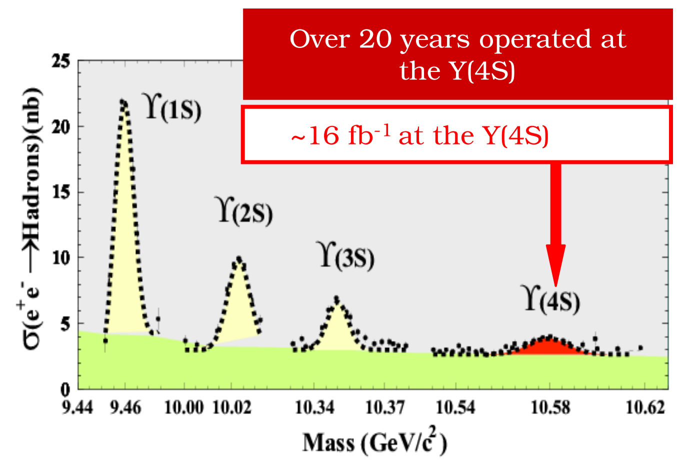
Conclusions

- An important task of CLEO-c is to calibrate and validate LQCD.
- Charm leptonic decays provide particularly stringent tests.
- Current precision of CLEO-c and LQCD results is comparable. CLEO-c results are statistically limited; LQCD results are limited by systematic uncertainties.
- Expect a three fold increase in the size of CLEO-c data sample and a complete suite of leptonic and semileptonic measurements in the next few years.
- On a longer time scale, BES III (China) should be able to improve CLEO-c results and further constrain the theory.

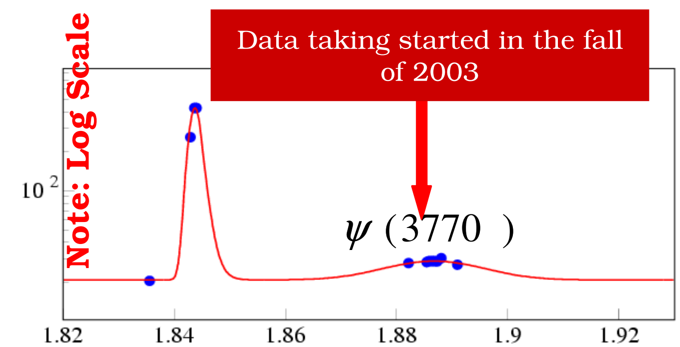
Additional Slides

CESR and CLEO

- The CLEO experiment is located at the Cornell Electron Storage Ring (CESR), a symmetric e^+e^- collider that operated in the region of the Upsilon resonances for over 20 years:
  - ✓ Max inst luminosity achieved: 1.3×10^{33} cm^{-2}s^{-1}
  - ✓ Total integrated luminosity at the Υ(4S): 16 fb^{-1}
  - ✓ Lots of important discoveries, e.g., Υ(nS), $b\to s\gamma$, $b\to uW$.



- In 2003, CLEO started running at the $\psi(3770)$, ~40 MeV above DD production threshold, and slightly higher energies for D_S studies.



- Transition from CESR to CESR-c:
  - ✓ 12 wigglers are installed to increase synchrotron radiation/beam cooling
  - ✓ Max luminosity achieved: ~7×10^{31} cm^{-2}s^{-1}

Why a Charm Factory?

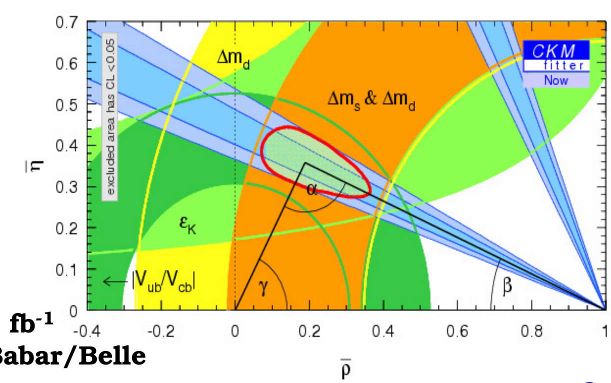
The main task of the CLEO-c open charm program:

Calibrate and Validate Lattice QCD

- Help heavy flavor physics constrain the CKM matrix now:
  - ✓ Precision tests of the Standard Model or
  - ✓ Discovery of new physics beyond the SM in *b* or *c* quark decays

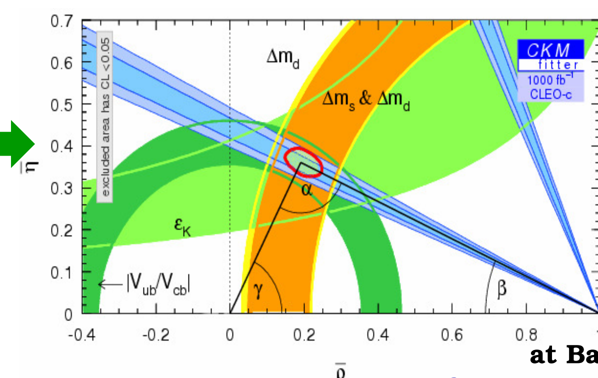
Difficulty: hadronic uncertainties complicate interpretation of exp. results

A realistic example using recent CKM status (new B_s mixing results are not included):



200 fb^{-1} at Babar/Belle

Reduce theory error on B form factors and B decay constants using tested LQCD



500 fb^{-1} at Babar/Belle

- Help LHC search for and interpret new physics (future)

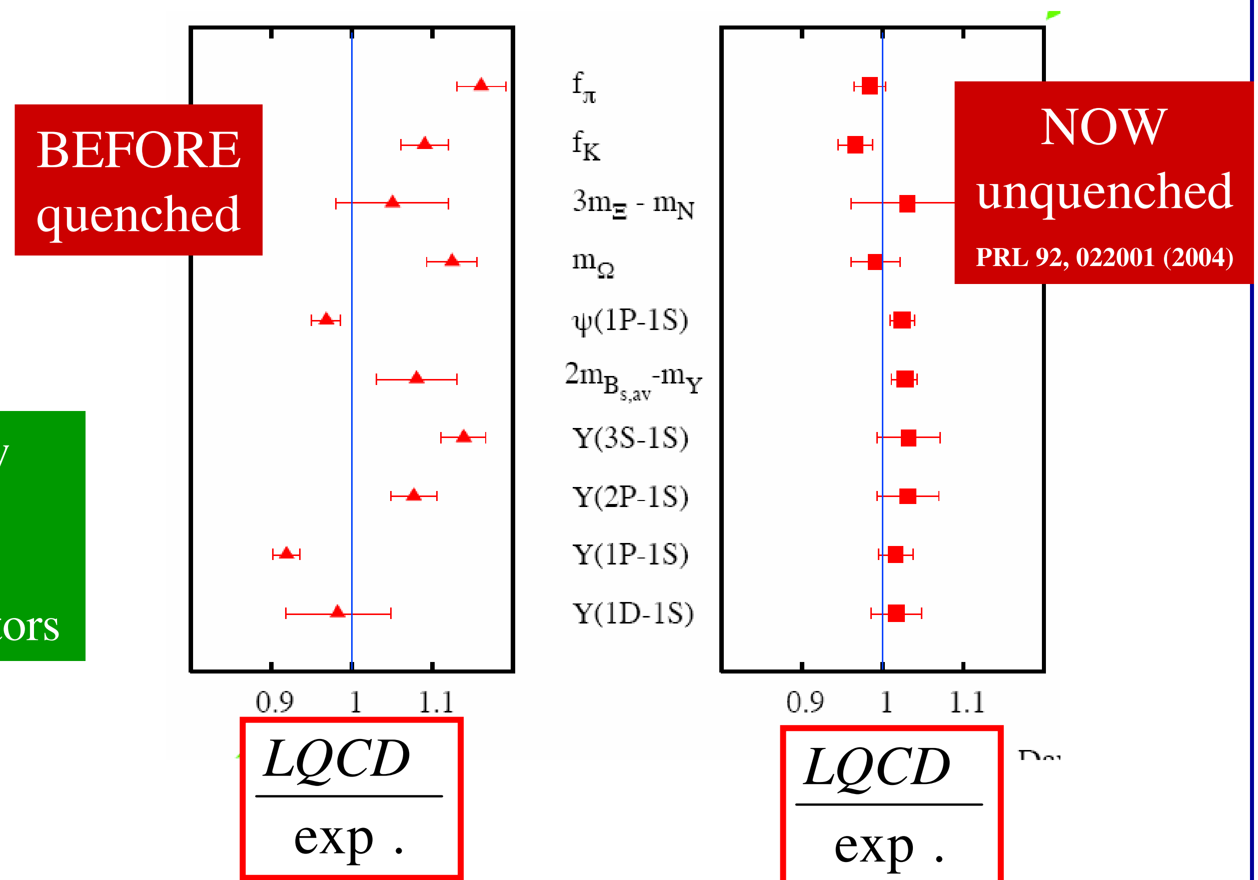
Why now?

- C. Davies opened her talk in Lisbon at EPS-2005:
  "There has been a revolution in LQCD…"

LQCD demonstrated that it can reproduce a wide range of mass differences and decay constants in unquenched calculations.
These were postdictions.

Testable **predictions** are now being made for:
Decay constants f_D and f_B;
D and *B* Semileptonic form factors

CLEO-c can test f_D and *D* semileptonic form factors

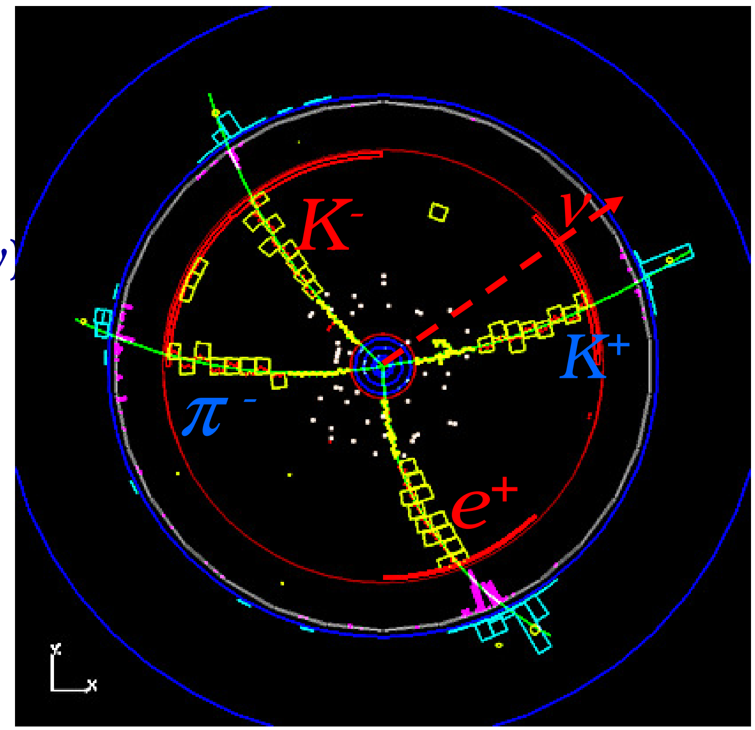


Tagging at the $\psi(3770)$

- The $\psi(3770)$ is about 40 MeV above the DD pair threshold ($\vec{P}_D = -\vec{P}_{\bar{D}}$)
- One of the two D's is reconstructed in a hadronic "tag" mode (e.g., $K^+\pi^-$). Two key variables:
  - ✓ $M_{bc} = \sqrt{E_{beam}^2 - P_{candidate}^2}$
  - ✓ $\Delta E = E_{candidate} - E_{beam}$
- From the remaining tracks and showers the semileptonic decay is reconstructed (e.g., $K^- e^+ \nu$)
- $U \equiv E_{miss} - |\boldsymbol{P}_{miss}|$ is used to identify signal, where E_{miss} and $\boldsymbol{P}_{miss}$ are the missing energy and momentum approximating the neutrino E and $\boldsymbol{P}$. The signal peaks at zero in U.
- Full event reconstruction allows to measure any kinematic variable with no ambiguities and with high precision

$\psi(3770) \to D^0 \bar{D}^0$

$\bar{D}^0 \to K^+\pi^-$, $D^0 \to K^- e^+ \nu$



D_S Tags at 4170